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AN EXAMINATION OF UNDERWAY REPLENISHMENT SEAKEEPING CRITERIA

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ABSTRACT

Underway Replenishment (UNREP) is an important operation for sustained naval operations. When evaluating Underway Replenishment operations, it is necessary to consider the main factors that reduce operability. The main sources of degradation identified in this report are: ship-to-ship interaction, equipment limits, and human factors. This report examines these sources and provides a method for generating criteria sets for operability evaluations. The example criteria sets developed represent the three different aspects of UNREP and use the presented threshold values. Though comprehensive analysis is suggested, various assumptions are made to allow analysis of cases where the details of the ship configuration are unknown. The effects of these assumptions are explained.

RÉSUMÉ

Le ravitaillement à la mer est important dans le cas d'opérations navales prolongées. Dans l'évaluation des opérations de ravitaillement à la mer, il faut prendre en considération les facteurs principaux gênant l'aptitude à la conduite. Les causes principals de dégradation mentionnées dans le rapport sont les suivantes: l'interaction hydrodynamique de deux navires, seuils de tolérance de l'équipment et facteurs humains. Le rapport examine ces causes et présente une méthode pour l'établissement de séries de critères servant à l'évaluation de l'aptitude à la conduite. Les séries de critères données en exemple s'appliquent aux trois différents aspects du ravitaillement à la mer et utilisent les valeurs de seuil présentées. Bien que l'on préconise une analyse détaillée, on fait certaines suppositions en vue de l'analyse de cas où la configuration des navires ne serait pas connue en détail. Les effets de ces suppositions sont expliqués.

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NOTATION

CONREP	Connected Replenishment
DREA	Defence Research Establishment Atlantic
DTRC	David Taylor Research Center
FAS	Fuelling At Sea
GLFE	General Lateral Force Estimator
H	Water depth (m)
H_{up}	Water depth corresponding to L_{up} in shallow water calculations (m)
L_{up}	Upper limit on lateral separation.
L_{low}	Lower limit on lateral separation.
L_{sep}	Desired lateral distance between ships
LFE	Lateral Force Estimator
MIF	Motion Induced Fatigue
MII	Motion Induced Interruptions
MSI	Motion Sickness Incidence
PTO	Percent Time Operable
RAS	Replenishment at Sea
rms	Root Mean Square
SOWM	Spectral Ocean Wave Model
SSA	Significant Single Amplitude
STREAM	Standard Tensioned Replenishment Alongside Method
UNREP	Underway Replenishment
VERTREP	Vertical Replenishment
VLS	Vertical Launch System
W	Vertical cargo window
x	X coordinate of point of interest.
y	Y coordinate of point of interest.
Y_{rel}	Lateral relative motion between ships.
Y_{sep}	Initial lateral distance between ship connect points.
z	Z coordinate of point of interest.
Z_{rel}	Vertical relative motion between ships.
Z_{sep}	Initial vertical distance between ship connect points.
α	Highline slope.
η_i	Response in i direction

Super-/ sub-scripts

$_{deck}$	Point on deck edge.
$_{high}$	Point on highline
$_i$	1 surge; 2 sway; 3 heave; 4 roll; 5 pitch; 6 yaw
$_R$	UNREP connection point on receiving ship
$_S$	UNREP connection point on supply ship
$*$	Coordinate location after rotation.

Coordinate system: x along hull centerline, positive forward; y positive to port; z positive up from baseline.

1 INTRODUCTION

Underway Replenishment (UNREP)[1] describes the transfer of fuel, munitions, supplies, and personnel from one vessel to another while ships are at sea. Underway Replenishment is conducted as a combination of one or more of three methods: Connected Replenishment (CONREP)[2], Fuelling at Sea (FAS)[3], and Vertical Replenishment (VERTREP)[4].

Underway replenishment operations are very important because they allow ships to remain at sea for prolonged periods of time. The ability of a Navy to project seapower and conduct sustained operations in remote ocean regions is directly linked to its UNREP capability. Navies without UNREP capability must return to port when fuel or cargo supplies become depleted.

Underway Replenishment evolutions are manpower intensive and are particularly sensitive to degradation in heavy seas due to excessive ship motions. Possible sources of degradation include strong winds, ship-to-ship hydrodynamic interaction, course keeping difficulties, motion sickness, heavy seas, and slippery decks. For this report, the degradation sources are grouped as relating to either ship-to-ship interactions, equipment factors, or human factors. The ship-to-ship related degradations are due to the motions of the connect points, suction forces, and ship separation. The equipment factors include pallet control, strikedown cranes, and cargo touchdown. The human factors considered are transverse and longitudinal Motion Induced Interruptions (MII)[1] and General Lateral Force Estimator (GLFE), Motion Sickness Incidence (MSI)[2] and UNREP station submergence. GLFE models the local acceleration used for calculating MII, which occur when ship motions cause personnel to slide or stumble. GLFE can also be used as a criterion for equipment factors, though no such limits are presently available.

2 SHIP-TO-SHIP DEGRADATION

Whenever ships operate in close proximity to one another, e.g. during UNREP operations, they become hydrodynamically linked. The motion of one ship will influence

[1] Replenishment at Sea (RAS) in Canadian naval terminology. This paper is a continuation of work at DTRC and the Canadian equivalent of the U.S. Navy terms will be given in footnotes.

[2] Replenishment at Sea Solids (RAS SOLIDS)

[3] Replenishment at Sea Liquids (RAS LIQUIDS)

[4] Same in both U.S. and Canadian navies.

Table 1: Ship-to-ship degradation sources with applicable criteria

EVENT	CRITERION	THRESHOLD	APPLICABLE
Rig and line failure; collision	Relative lateral motion between ships	Rig, speed, and environment dependent	CONREP; FAS
Cargo striking deck	Relative vertical motion between two points on same ship	Configuration dependent	CONREP

the motion of the other without any mechanical connection. The amount of ship-to-ship interaction depends on ship speed, separation distance, relative position, and water depth. The main mechanism of hydrodynamic linking is the interaction of the ships' pressure fields as they operate in close proximity; ships may experience repulsive or attractive forces and moments depending on their relative position. These forces and moments increase with increasing speed and decreasing water depth[3]. If ship separation becomes too small, the ships could collide due to venturi suction force before corrective action can be taken.

Papers by Fang and Kim[4], Ohkusu[5], and Tuck and Newman[6] describe theories for calculating motions of hydrodynamically linked bodies. Though the theory is well established, such seakeeping programs are not trivial or in common use, and so ship-to-ship interaction is usually neglected in seakeeping evaluations. See Table 1 for a general overview of ship-to-ship degradation sources.

2.1 Relative Motion

The relative motion between the ships affects the passing of cargo and ship separation distance. Relative vertical motion affects the cargo/deck clearance and may cause the cargo to strike the ship. Lateral relative motion affects course keeping and may part lines and hoses if too great, or cause a collision if too small.

The linearized relative motion between the two ships is given by Equations 1 and 2 from Fang and Kim[4]. The relative motion is the variance of the difference between the points, not the absolute difference. With two-ship seakeeping programs, both ships move, but with one-ship seakeeping programs one ship moves, as effects due to the other ship are not included.

$$Z_{rel} = (\eta_3^S - x_S\eta_5^S + y_S\eta_4^S) - (\eta_3^R - x_R\eta_5^R + y_R\eta_4^R) \tag{1}$$

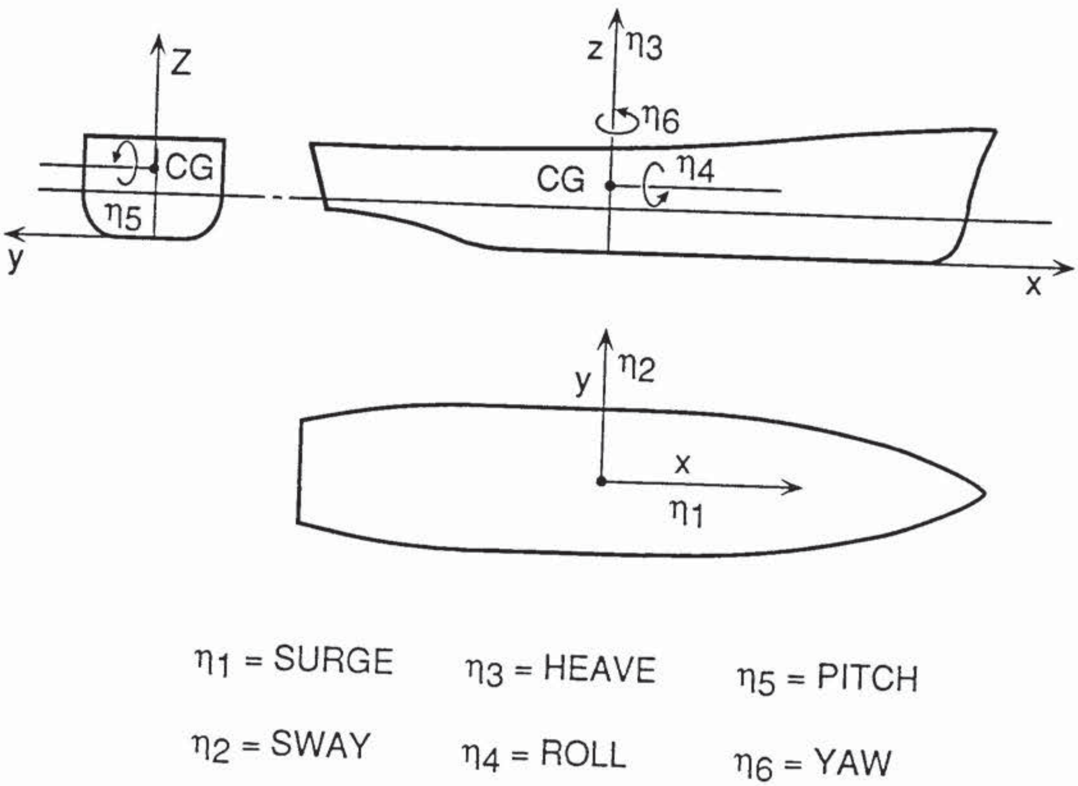

Figure 1: Single ship coordinate system.

$$Y_{rel} = (\eta_2^S + x_S\eta_6^S - z_S\eta_4^S) - (\eta_2^R + x_R\eta_6^R - z_R\eta_4^R) \tag{2}$$

The points $(x, y, z)_S$ and $(x, y, z)_R$ are the connection points on the supply and receive ships respectively. Figure 1 defines the coordinate system. The motions for the supply and receive ship are denoted by η_i^S and η_i^R respectively.[5]

The coordinates of the CONREP/FAS points change with different ship classes. Connection points can be defined by examining drawings[7] or pictures of the ship in question, and manuals on UNREP[8]. An initial guess for unknown ship configurations is three CONREP/FAS points at stations 5, 10, and 15[6]. The height of the CONREP connection points should be no less than 5.1 m above the associated

[5] 'i' is 1 surge; 2 sway; 3 heave; 4 roll; 5 pitch ; 6 yaw.

[6] The forward perpendicular is station 0, and the aft perpendicular is station 20.

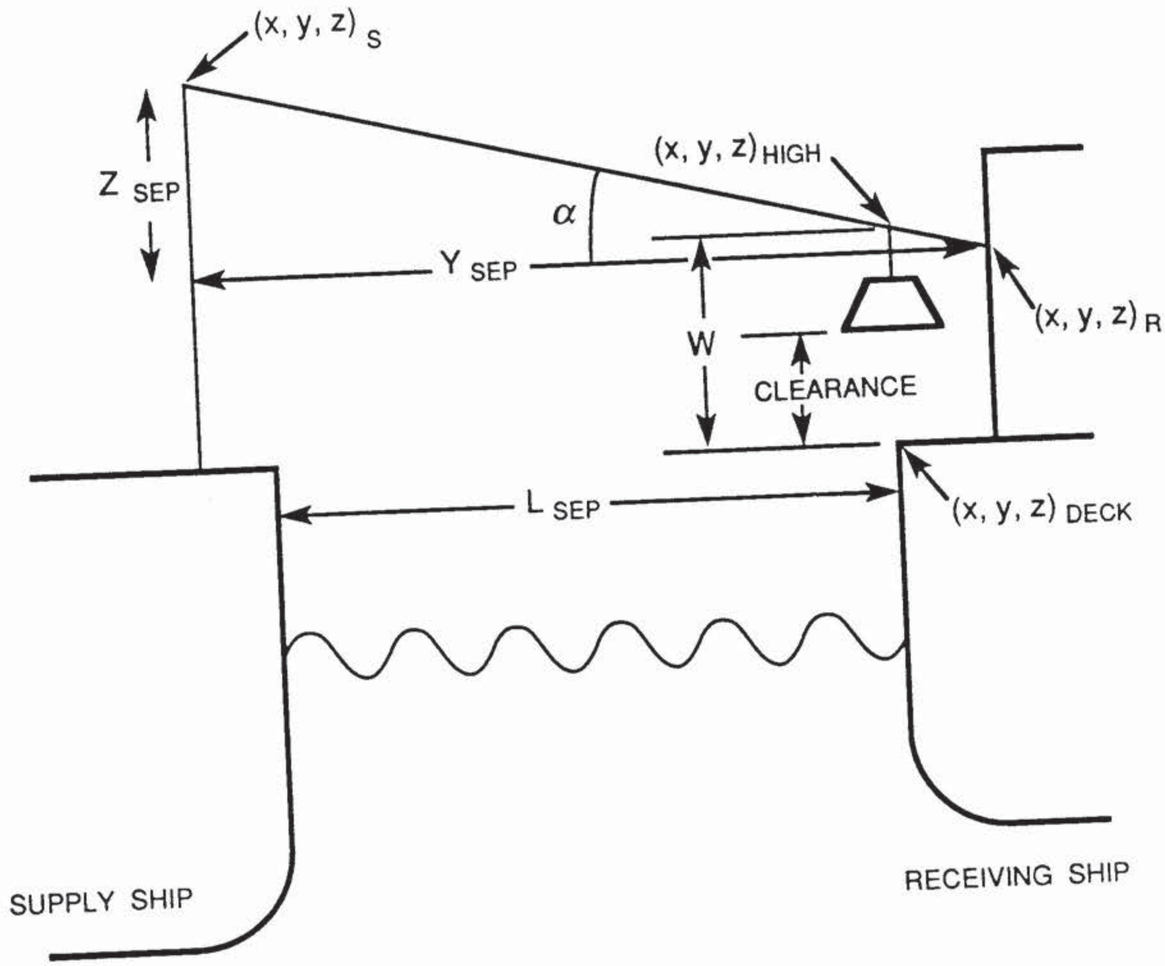

Figure 2: Definition of points and lengths for ship-to-ship interaction.

landing deck locations[8].

2.1.1 Cargo Clearance

In heavy seas, ship motions can prevent cargo from being sent or received due to lack of deck clearance. The vertical 'window' the cargo has to fit through is the vertical distance from the highline to the landing deck edge, see Figure 2.

Equation 3 gives the highline slope[7], α, using the relative motion between the ships, Z_{rel} and Y_{rel}, Equations 1 and 2, and the initial point separation distances,

[7]Actually slope of highline projection on y-z plane

Z_{sep} and Y_{sep}.

$$\alpha = \arctan\left(\frac{Z_{sep} - Z_{rel}}{Y_{sep} + Y_{rel}}\right) \tag{3}$$

The highline position is found using Equation 4. The $*$ indicates the location after rotation, e.g. roll, using the semi-linear equations in Appendix A. The rotations should be done using the transfer functions, rather than the root mean square (rms) values, to preserve the phase relation between the motions.

$$z^*_{high} = z^*_R + (y^*_{deck} - y^*_R)\tan\alpha \tag{4}$$

The final window is the highline position minus the landing deck edge position. Using the semi-linearized equations from Appendix A, the window height, W, is Equation 5.

$$\begin{aligned} W &= (z^*_{high} - z^*_{deck}) \\ &= (z_R - z_{deck})(\cos\eta_5\cos\eta_4 + \sin\eta_4\tan\alpha) + \\ &\quad (y_R - y_{deck})(\sin\eta_4 - \cos\eta_6\cos\eta_4\tan\alpha) + \\ &\quad (x_{deck} - x_R)(\sin\eta_5 + \sin\eta_6\tan\alpha) \end{aligned} \tag{5}$$

The cargo height is the distance from the highline to the bottom of the pallet. If this distance is greater than the available window a collision will occur. A typical cargo height is 2.7 m. The cargo clearance is the distance between the bottom of the pallet and landing deck edge. All three of these points, highline, pallet bottom and landing deck edge, are considered to be on the same ship. The relative motion between two points on the same ship is found using Equations 1 and 2 where both points are on the the same ship.

Operability analysis requires a statistical expression of window height or cargo clearance. If a Rayliegh distribution of extreme values is assumed, and the maximum amplitude is taken to be equivalent to the 1/1000th (largest) amplitude, then the rms value can be assumed to be 0.26904 times the maximum value. The significant single amplitude value is simply twice the rms value, or 0.53808 times the maximum.

2.1.2 Assumptions

Rigorous calculation of the window height using the transfer functions may not be possible. The two point relative motion criteria may be converted to other limiting motions by various assumptions.

The highline slope can be assumed constant and equal to its static value. Then Equation 5 can be solved for a combination of roll and pitch angle by setting the window height equal to the cargo height. Equation 5 is also greatly simplified by assuming the highline slope is zero near the receiving ship due to line sag. This is a conservative approach and requires no knowledge of the supply ship. In both cases, Equation 5 can be solved in terms of roll only by assuming pitch and yaw are small ($\cos\eta_5 \approx \cos\eta_6 \approx 1$).

Neither a swinging load nor the actual catenary of the highline is taken into account. These effects would tend to reduce the window height, though to an extent which is beyond the scope of the model presented here.

2.2 Lateral Separation

For most UNREP evolutions, the ships are physically connected with a replenishment rig. Many different rigs, such as Burton, housefall, jackstay, and tensioned, exist and are in use[7]. The U.S. Navy and, to a limited extent, the Canadian Navy use the Standard Tensioned Replenishment Alongside Method (STREAM) rig in addition to the others mentioned.

The specifications for UNREP equipment are demanding, being empirically determined as fully operable through Sea State five. Through years of experience, tension and loading requirements as applied to Navy replenishment rigs have been found to meet those specifications. Nevertheless, if the ships drive apart and the rig fails or the lines part, replenishment cannot occur. Relative lateral separation is a criterion that models this event. Table 2 shows the upper normal, lower normal, and derived "optimum" and "near maximum" separation distances for the various rigs. The large distance between the optimum and upper normal limits suggest the Percent Time Operable (PTO) drops off gradually.

The lateral separation required between the two ships depends on environmental conditions, size of ships involved, speed, rigs used, and water depth. Using the guidelines presented in ATP 16(B)[8] the following procedure for determining separation distance and relative lateral separation is presented. This procedure is for the purposes of operability analysis and should not be used operationally.

1. The distance depends on the rig used. Use the least value with multiple rigs. The distance should not exceed that specified for non-tensioned rigs if present.

Table 2: Lateral separtion distances based on rig and ship type. (Adapted from Reference [8])

TYPES OF RIG	DISTANCE	SHIP TYPE		
		Destroyers and smaller	Cruisers and larger	Carriers
Missile/Cargo STREAM	Upper Lower "Optimum" "near maximum"	60.9 m 24.3 m 42.6 m 54.8 m	60.9 m 24.3 m 42.6 m 54.8 m	60.9 m 30.4 m 45.7 m 55.8 m
Burton Housefall Mod Housefall Synthetic Highline	Upper Lower "Optimum" "near maximum"	30.4 m 24.3 m 27.4 m 29.4 m	36.5 m 24.3 m 30.4 m 34.5 m	42.6 m 30.4 m 36.5 m 40.6 m
Fuel STREAM	Upper Lower "Optimum" "near maximum"	54.8 m 24.3 m 39.6 m 49.7 m	54.8 m 24.3 m 39.6 m 49.7 m	54.8 m 24.3 m 39.6 m 49.7 m
Nontensioned Spanwire Fuel Rig	Upper Lower "Optimum" "near maximum"	30.4 m 24.3 m 27.4 m 29.4 m	36.5 m 24.3 m 30.4 m 34.5 m	42.6 m 30.4 m 36.5 m 40.6 m
Closed-in Fuel Rig	Upper Lower "Optimum" "near maximum"	24.3 m 18.2 m 21.3 m 23.3 m	30.4 m 18.2 m 24.3 m 28.4 m	

2. The optimum distance is between the upper and lower normal limits, L_{up} and L_{low}. Assume the optimum distance, L_{sep}, is the average of the upper and lower limits.

3. The maximum allowable relative lateral separation, L_{rel}, is the difference between the average and upper limits. This distance is converted to a statistical basis by assuming a one-in-thousand chance of exceedence (multiply by 0.26904 for rms, 0.53808 for SSA). When using a single ship seakeeping code this distance should be halved because only one ship is present.

$$L_{sep} = 0.500(L_{low} + L_{up}) \tag{6}$$
$$L_{rel} = (L_{up} - L_{sep}) \tag{7}$$

These values, L_{sep} and L_{rel}, are modified based on operational considerations. The distance should be near the maximum when:

1. Ship speed is 15 knots or greater.
2. Ships are yawing excessively.
3. Transfer stations are located on the quarter of large ships, especially when the ship alongside is a smaller unit.

For these cases use the following equation for L_{sep}.[8]

$$L_{sep} = (L_{low} + 5L_{up})/6 \tag{8}$$

In shallow water, depth $\leq$ 64 m, the separation distance should increase as water depth decreases[8]. The separation distance for a given water depth, H, is given by Equation 9 where H_{up} is the water depth corresponding to the upper normal separation. The actual value of H_{up} is not specified by Reference [8] but should be large enough the minimise shallow water effects. Taking the side force coefficient from Yeh[9] and assuming a maximum draft of 11 m for the ships involved, the recommended value for H_{up} is 48 m.

$$L_{sep} = \frac{L_{up} + L_{low}}{2} + \left(\frac{H - 64}{H_{up} - 64}\right)\frac{L_{up} - L_{low}}{2} \tag{9}$$

The effect of span wire tension is typically neglected in the motion calculations though some danger exists during tensioning and detensioning STREAM rigs.

[8]The choice of 5/6 as "near maximum" was arbitrary.

2.2.1 Assumptions

The use of a single ship seakeeping code requires some assumptions to allow use of lateral separation criteria. In this case, the other ship is assumed to have no oscillatory motion, i.e. constant forward speed is the only motion. As a result Equations 1 and 2 simplify to the linearized equations for absolute motion. The lateral motion limit is then half of the two ship value. This assumes that each ship contributes equally to the relative motion between them. The limit could also reasonably be split by displacement ratio or underwater profile area ratio. As mentioned elsewhere, using a single ship seakeeping code ignores any interaction effects on relative motion.

3 EQUIPMENT FACTORS

Equipment factors degrade operability by limiting cargo movement. This is more of a problem for the receiving ship than the supply ship. The factors considered in this report are pallet control, strikedown cranes, and cargo touchdown. Table 3 gives the limiting motions and threshold values associated with typical U.S. Navy equipment.

Once on board the ship, the cargo is loaded on pallets and manhandled into place. Loss of pallet control could result in crew injury and cargo damage. The ability to keep a pallet under control depends upon the type of pallet and number of personnel available. Pallet limits are usually given as the greatest slope at which slipping begins with a standard allotment of personnel. Wet deck slopes can be estimated using a percentage reduction of the dry deck slopes. If the deck condition of the limit is unknown, dry decks should be assumed, because erroneously classifying a wet deck as dry will lead to an excessively strict limit estimate. The maximum dynamic slip angles are converted to rms or SSA values in the same manner as window and cargo clearances. See Table 4 for dynamic limits for various pallets used in the USN fleet.

Strikedown cranes are usually associated with the reloading of Vertical Launch Systems (VLS). While roll and pitch are perhaps not the best limiting motions for strikedown, they are currently used as criteria[10]. A roll value of 5.0° and pitch value of 2.0° single significant amplitude are generally accepted as the limiting values.

Cargo touchdown describes placing cargo safely on the deck during VERTREP. The limiting motions are those used for helicopter landing[11], absolute vertical displacement and velocity. Absolute motions are used because the ship is considered moving with respect to a stationary helicopter.

The absolute vertical displacement limit is the same as helicopter landing because in both cases something is being placed on the deck. The absolute vertical velocity limit for helicopter landing models the ability of the landing gear to absorb the landing, and is used here to model impact velocities. The limit for UNREP depends on the cargo; obviously, missiles require a lower limit than sacks of beans.

Table 3: Equipment factors degradation sources with applicable criteria

EVENT	CRITERION	THRESHOLD	APPLICABLE
Pallet slipping	roll; pitch	Pallet and deck condition dependent	CONREP; VERTREP
VLS strikedown	roll pitch	5.0° SSA 2.0° SSA	CONREP; VERTREP
Cargo touchdown	Abs. vert. displ. Abs. vert. velocity	1.43 m SSA 2.13 m/sec SSA	VERTREP

Table 4: Dynamic roll and pitch limits for various dollies and handtrucks (Reference [11]).

TYPE	MEN	DRY	WET	COMMENT
Missile handling dolly	10	$6^{\circ *}$–$9^{\circ \dagger}$	$6^{\circ *}$–$7.5^{\circ \dagger}$	Missile or equivalent weight (Tartar missile)
Handtruck (missile)		$5^{\circ *}$–$10^{\circ \dagger}$	$5^{\circ *}$–$8^{\circ \dagger}$	
Handtrucks (container)	9	$3^{\circ *}$–$6^{\circ \dagger}$		Two per container
Handpallet transporter	4 4	$3^{\circ *}$ $0^{\circ *}$		1,000 kg load. 1,500 kg load. Unstable at 8°.
Walkie type pallet truck (battery)		$10^{\circ *}$		825 kg load unstable at 17°.
Generic		$6^{\circ *}$		Design goal.

Note: Limits are assumed maximum single amplitude.

∗ Limit refers to 100 percent operable.

† Limit refers to 0 percent operable.

4 HUMAN FACTORS

Human limitations are important when evaluating UNREP operability because it is manpower intensive. Moving heavy cargo loads is dangerous and the crew should be at peak capability. Any stumbling or lurching can degrade capabilities. Traditional 'human factors' criteria are lateral and vertical accelerations at the pilot house. The two main problems with these criteria are the inappropriate location and the applicability of accelerations. Most of the personnel involved are near the the UNREP connect points to help disconnect the cargo from the highline and move the pallets, not in the pilot house. Accelerations are more appropriate to assessing motion sickness than stumbling or loss of balance. To improve operability calculations, human factors criteria should be based on loss of balance events where personnel are working.

Crewmembers working at replenishment stations which are located on exposed weather decks are subject to performance degradations due to ship motions, spray, and green water. Motion Induced Interruption (MII) is a measure of the number of expected stumbles and/or slides in a given time[1]. Both lateral and longitudinal MII are used to account for people facing different directions and moving around during UNREP evolutions. Table 5 gives an overview of the events and applicability of human factors criteria. Table 6 gives the MII and GLFE values associated with various risk levels[12].

Table 5: Human factors degradation sources with applicable criteria

EVENT	CRITERION	THRESHOLD	APPLICABLE
Stumbling (loss of balance and sliding)	Lateral and longitudinal MII	0.1/min	CONREP; FAS; VERTREP
Motion sickness	MSI	Undefined	CONREP; FAS; VERTREP
Fatigue	MIF	Undefined	CONREP; FAS; VERTREP
Station submergence	Relative vertical motion	0.5/hour	CONREP; FAS

Table 6: Risk levels associated with MII and GLFE values

Risk Level	MII/min	GLFE (G) rms
Possible	0.10	0.08
Probable	0.50	0.10
Serious	1.44	0.12
Severe	2.61	0.14
Extreme	4.00	0.16

Motion Sickness Incidence (MSI) and Motion Induced Fatigue (MIF) are included to model the effect of the sailor whose mental state is degraded by ship motions[13]. These measures do not include habituation effects and are not as well understood as GLFE or MII; in fact, no limits presently exist for MIF. Furthermore, these are long term effects and may not be applicable to short duration UNREPs. They can be applied at the bridge to measure pilot degradation and at the UNREP stations for long UNREPs. In any event, they are better than raw accelerations.

The heavy loads and awkward positions required for UNREP demand a low risk level be used when picking criteria threshold.

5 CALCULATION OF OPERABILITY

The seakeeping qualities of a ship can be conveniently predicted using modern strip theory motion programs, such as DREA's SHIPMO[14, 15] or DTRC's Standard Ship Motion Program (SMP84)[16, 17]. Modelling ship-to-ship interaction requires a code specially designed for such calculations[4]. The main difference between using a single or two ship code for operability calculations is the resulting response transfer functions, but not the criteria set used. The reason is that the limiting events are the same in both cases, whereas the motions are not.

Work by McCreight and Stahl[18] incorporates environmental data with strip theory motion predictions to calculate Percent Time Operability (PTO) which allows relative comparison of operability at specific geographic locations. The accuracy and validity of the PTOs are based on the accuracy of the transfer functions, the motion criteria sets, and wave climatology used in the evaluation. The PTO is the sum of the probabilities of occurrence for the spectra where none of the motion limits are exceeded. The probability of failure is the sum of the probabilities of occurrence for

each spectrum for which the motion limits are exceeded..

The Seakeeping Evaluation Program (SEP)[19] calculates operability using as criteria: roll; pitch; keel slamming; deck wetness; absolute vertical displacement, velocity, and acceleration; relative vertical displacement and velocity; absolute lateral acceleration; Lateral Force Estimator (LFE); and fin angles. SEP uses the Spectral Ocean Wave Model (SOWM) data base to model the seaway. The SOWM data base contains archived wind data and hindcast wave fields for approximately 1500 locations throughout the northern hemisphere.

Obviously some of the desired criteria are unavailable with SEP. Multiple runs are necessary to identify non-limiting criteria, because only one criterion per point per run is allowed. The criteria set chosen must acknowledge these limitations and will necessarily be composed of the criteria available to the operability analysis program. This report will assume the most general case and the reader should ignore that which is not possible for his situation.

6 DERIVATION OF CRITERIA SETS

Criteria sets indicate which motions degrade operations and at what rate operations degrade with respect to motions. The first step in generating a criteria set is determining the applicable degrading events for that mission. The applicability of the different events is given in Tables 1, 3, and 5. Every source should be identified, even if the criterion is not well defined. This will show what has been considered and how the assumptions affect the results.

The failure limits for each source can be identified based on experience. More than one degradation source may have the same limiting motion, in which case the lowest failure limit is used for that motion. The criteria sets are lists of limiting motions, not degradation sources, so each limiting motion should appear only once for each position. This is the most general criteria set for a mission; the set actually used depends upon what is available in the operability analysis program.

In essence, the criteria set generation process is one of successive filtering. First extraneous degradation sources are filtered out, then redundant limiting motions, and finally unavailable criteria.

Combined UNREP method, e.g. VERTREP/FAS, criteria sets are easily generated by applying this methodology again to the combination of the individual CONREP, FAS, and VERTREP criteria sets.

6.1 Speed-Heading Weights

Most operability programs allow the speed-heading combinations to be weighted to model an operational profile. If this is possible, the following should be kept in mind. Underway replenishment is conducted at the heading that allows station keeping with a minimum strain on the rigs.This usually means the heading of least roll, which is head seas; however, in heavy seas a following seas course may prove advantageous. To that end, only headings $\pm 30^\circ$ from the bow and stern should be considered.

The speed range is determined by the minimum speed to maintain control and the maximum speed without undesirable venturi effects. Speeds between 12 and 16 knots are generally acceptable. Speeds below eight knots are not advisable due to lack of rudder control. Speeds in excess of 16 knots may be used if lateral separation is increased. In general, only speeds between 10 and 15 knots are valid for UNREP. Speed should be decreased in shallow water.

7 CONNECTED REPLENISHMENT

Connected Replenishment includes the transfer of personnel, munitions, or cargo between two ships and is the most general replenishment case. Connected replenishment requires the delivery and receiving ship to steer parallel courses while operating in close proximity to one another. There is little margin for error in terms of ship handling and collision avoidance between the two ships, which are less than one ship length apart. The stores are manhandled from place to place on pallets in a labour intensive process. As seen in Tables 1, 3, and 5, virtually all events degrade CONREP. The criteria set is generated as outlined in Section 6; a specific example follows.

7.1 Example

Consider the connected underway replenishment of a destroyer by a large stores ship. The following assumptions will be made:

1. Only missile/cargo STREAM rigs used.
2. Walkie type pallet truck on wet decks.
3. UNREP at speed of 15 knots in deep water.

4. Highline slope is constant and equal to initial static value.

Notional connect points are used here; a real analysis would use the actual connect points. The destroyer has three points and the stores ship has seven per side.

Table 7: Connect Replenishment example connection locations.

Destroyer				
Station	Padeye		Landing Deck Edge	
	Y (m)	Z (m)	Y (m)	Z (m)
2.5	0.0	18.3	2.5	12.0
9.0	5.6	17.6	8.0	12.1
17.0	0.0	17.6	6.0	12.1
Stores ship				
Station	Padeye		Landing Deck Edge	
	Y (m)	Z (m)	Y (m)	Z (m)
2.5 *	9.1	23.0	12.5	12.1
5.0	9.1	23.0	12.5	12.1
7.5 *	9.1	23.0	12.5	12.1
10.0	9.1	23.0	12.5	12.1
12.5 *	9.1	23.0	12.5	12.1
15.0	9.1	23.0	12.5	12.1
17.5	9.1	23.0	12.5	12.1

* Stations connected with the destroyer.

Ship-to-ship interaction imposes both lateral and vertical relative motion limits. Separation distances are found in Table 2. The value chosen depends on the rig, the size of the ships involved, and the replenishment configuration. The separation distance for this example, 54.8 m, is the "near maximum" distance for "Destroyers and smaller" using a "missile/cargo STREAM" rig. The "near maximum" distance is chosen because the speed is 15 knots. Equation 7 yields a value of 6.1 m for L_{rel}. The statistical expression of relative lateral motion limit is 0.53808×6.1 m significant single amplitude, or 0.26904×6.1 m rms.

The highline slope is considered to be constant at its initial static value, so Y_{rel} and Z_{rel} in Equation 3 are zero. Finding Y_{sep} and Z_{sep} requires the knowledge of the beam and draft of both ships.

Table 8: Separation distances and highline slopes for Connected Replenishment example.

CONNECTION	Y_{sep} m	Z_{sep} m	α deg
2.5 – 2.5	67.2	1.7	1.45
9.0 – 7.5	61.6	2.4	2.23
17.0 – 12.5	67.2	2.4	2.04

Y_{sep} is the distance between connection points which is larger than the distance between the ships, L_{sep}, by the distance between the padeye and the half beam. The drafts are necessary so the z-coordinates can be taken from the waterline, which is a common reference line for both ships. Assume the draft of the destroyer is 6 m and beam is 18 m; the draft of the stores ship is 9 m and the beam is 25 m. Table 8 gives Y_{sep}, Z_{sep}, and α for the three connecting highlines. The three different slopes, α, are needed to calculate the cargo clearance at the three connect points.

Assume a cargo height of 2.7 m. This yields a cargo clearance of 3.6 m at station 2.5 and 2.8 m at stations 9 and 17. The significant single amplitude (SSA) two point relative vertical motion limit is 0.53808× cargo clearance. The rms value is 0.26904× cargo clearance. Simply using the smallest clearance value could be erroneous because a large limit in the bow may be exceeded more easily than a small limit near midships. The two point relative vertical motion criteria should be applied at the different stations.

Equipment limits show up as slide angles for the Walkie pallets. A glance at Table 4 reveals that there is no defined limit for Walkie type pallets on wet decks. In this case multiply the dry deck limit by 0.8167 to get a wet deck limit[9] and then multiply again by 0.53808 to convert the maximum single amplitude limit to a significant single amplitude (or by 0.26904 to convert to rms). This value is the limit for both roll and pitch.

The applicable degradation sources and their limiting motions and threshold values are given in Table 9.

None of the limiting responses are duplicated so this is the final criteria set subject to operability code restraints. Six points should be defined, three padeye points and three deck edge points. A two ship seakeeping program would allow the highline slope to be rigorously calculated using the transfer functions and may exhibit

[9]Factor of 0.8167 is average of wet/dry ratios for other cases.

Table 9: Connected Replenishment criteria.

Ship-to-ship interaction				
Separation distance		rel. lat. motion	3.3 m SSA	1.65 m rms
	(one ship	abs. lat. motion	1.6 m SSA	0.80 m rms)
Cargo clearance		2 pt. rel. vert. mot.		
		Station 2.5	1.9 m SSA	1.85 m rms
		Stations 9 and 17	1.5 m SSA	0.75 rms
Equipment factors				
Walkie type pallet truck slip angle		Roll	4.39°SSA	2.2°rms
		Pitch	4.39°SSA	2.2°rms
Human factors				
Stumbling		MII	0.5/min	
		GLFE	0.08 g SSA	0.04 g rms
		MSI	20% @ 4 hr	
		Submergence	0.5/hr	

decreased roll motion.

8 FUELLING AT SEA

Fuelling at Sea (FAS) is similar to CONREP and often conducted at the same time, but only fuel is transferred during FAS. The difficulties associated with ship handling and crew exposure to adverse conditions are still present. Equipment factors and cargo clearance do not become an issue, because only fuel is transferred. Only ship-to-ship and human factors degradations are applicable; see Tables 1 and 5. FAS is often conducted concurrently with CONREP. The process outlined in Section 6 is used in the following specific example.

8.1 Example

Consider the fuelling of a frigate by an aircraft carrier. The following assumptions will be made:

1. Only fuel STREAM rigs used.

2. UNREP at speed of 10 knots in 50 m deep water.

Example connection points are used here, a real analysis would use the actual connection points. The frigate has two points and the carrier has three per side.

Table 10: Fuelling at Sea example connection locations.

Frigate				
Station	Padeye		Deck Edge	
	Y (m)	Z (m)	Y (m)	Z (m)
9.0	5.6	17.6	8.0	12.1
17.0	0.0	17.6	6.0	12.1
Aircraft carrier				
Station	Padeye		Deck Edge	
	Y (m)	Z (m)	Y (m)	Z (m)
13.0	18.3	18.3	21.3	13.7
15.0	9.1	23.0	12.5	12.2
17.5	9.1	23.0	12.5	12.2

Separation distances are found in Table 2. The value chosen depends on the rig, the size of the ships involved, and the replenishment configuration. The separation distance for this example, 53.0 m, is calculated using the shallow water correction, Equation 9, for "Destroyer and smaller" using a "fuel STREAM" rig. The shallow water correction is used because the water depth is less than 64 m. L_{rel} is 7.6 m and the threshold value is 0.53808 × 7.6 m SSA, or 0.26904 × 7.6 m rms.

No cargo clearance or equipment factors limits are needed. In this case, the point locations on the aircraft carrier are not needed either if a one ship code is used. The limiting events with their threshold values are given in Table 11.

None of the limiting responses are duplicated so this is the final criteria set subject to operability code restraints. Four points should be defined, two padeye points and two deck edge points. The human factors criteria are calculated at the landing deck edge points.

Table 11: Fuelling at Sea criteria.

Ship-to-ship interaction			
Separation distance	rel. lat. motion	4.1 m SSA	2.05 m rms
(one ship	abs. lat. motion	2.1 m SSA	1.05 m rms)
Human factors			
Stumbling	MII	0.5/min	
	GLFE	0.08 g SSA	0.04 g rms
	MSI	20% @ 4 hr	
	Submergence	0.5/hr	

9 VERTICAL REPLENISHMENT

Vertical Replenishment (VERTREP) involves the use of helicopters to transport stores rather than cranes and cables between connected ships. VERTREP permits the total replenishment of ships in a dispersed formation which do not require fuel and has the major advantage of not requiring a physical connection between the supply and receiving ship. VERTREP may also be conducted concurrently with CONREP or FAS. A solo VERTREP criteria set is developed here.

Since VERTREP helicopters are often not maintained aboard the receiving ships, this study assumes that the helicopters were successfully launched from the supply ship. This may not be a valid assumption in the higher sea states. The delivery of cargo only requires that the helicopter retains the capability to hover above the deck to raise or lower cargo pallets. In this case the human factors calculations should be carried out at the helicopter or VERTREP pad instead of connection points. Criteria similar to helicopter touchdown are employed to avoid cargo damage.

A major factor in VERTREP is the requirement of a high relative wind to facilitate hovering of the helicopter. Optimum and non-optimum relative wind envelopes for VERTREP exist. The optimum wind envelope is $\pm 30^\circ$ from the bow and 15 to 30 knots; see Figure 3. The non-optimum wind envelope is $\pm 90^\circ$ from the bow and 15 to 30 knots; see Figure 4.

The less restrictive non-optimum envelope gives the total possibility of conducting VERTREP, while the optimum wind envelope identifies the conditions where no degradation due to relative wind occurs. These envelopes may be significantly changed by helicopter-superstructure interaction, which may reduce the size of the

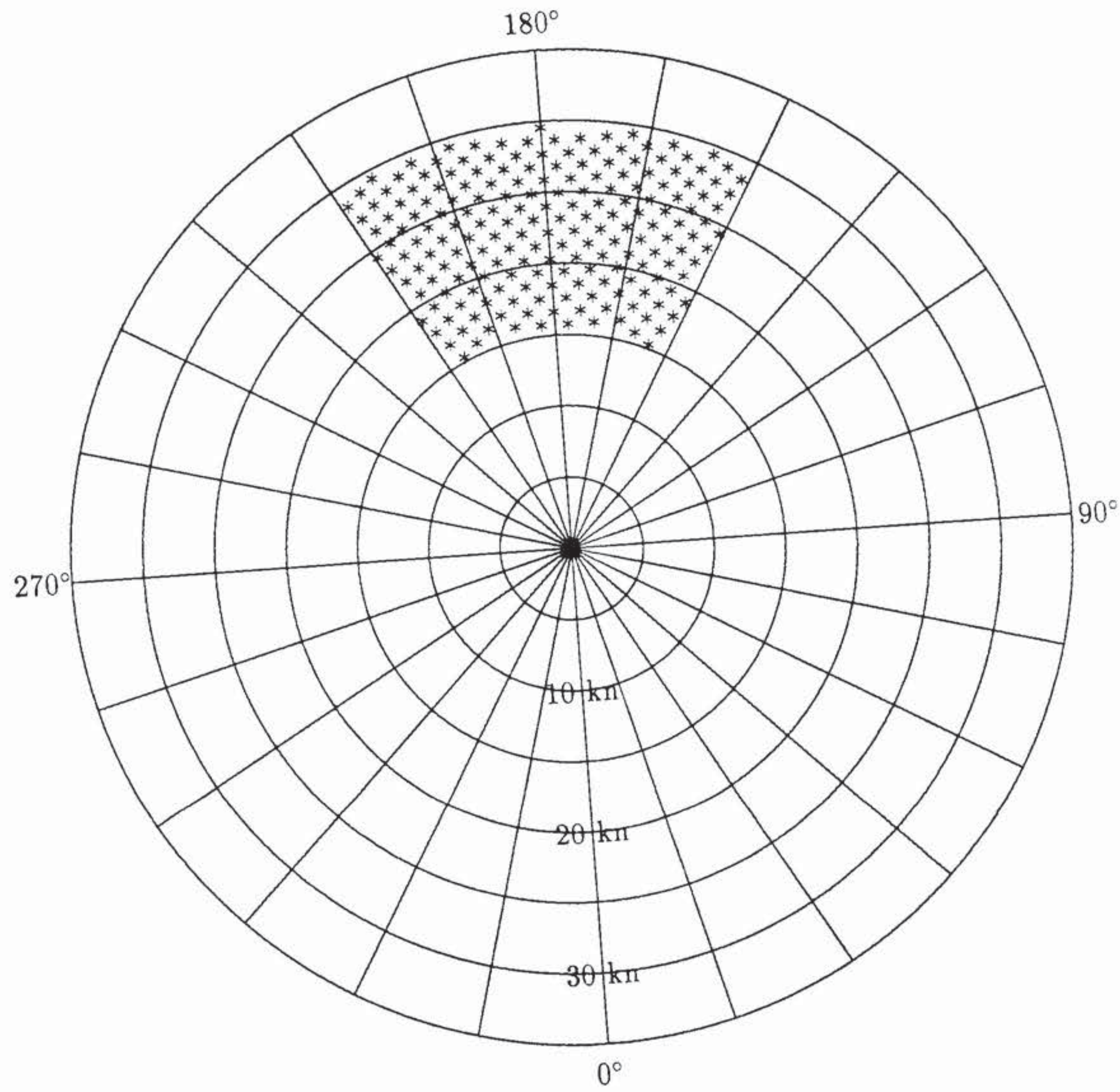

Figure 3: Optimum relative wind envelope. Shaded region is operable. Angles are ship heading relative to waves; head seas is 180°. Radial values are ship speed in knots.

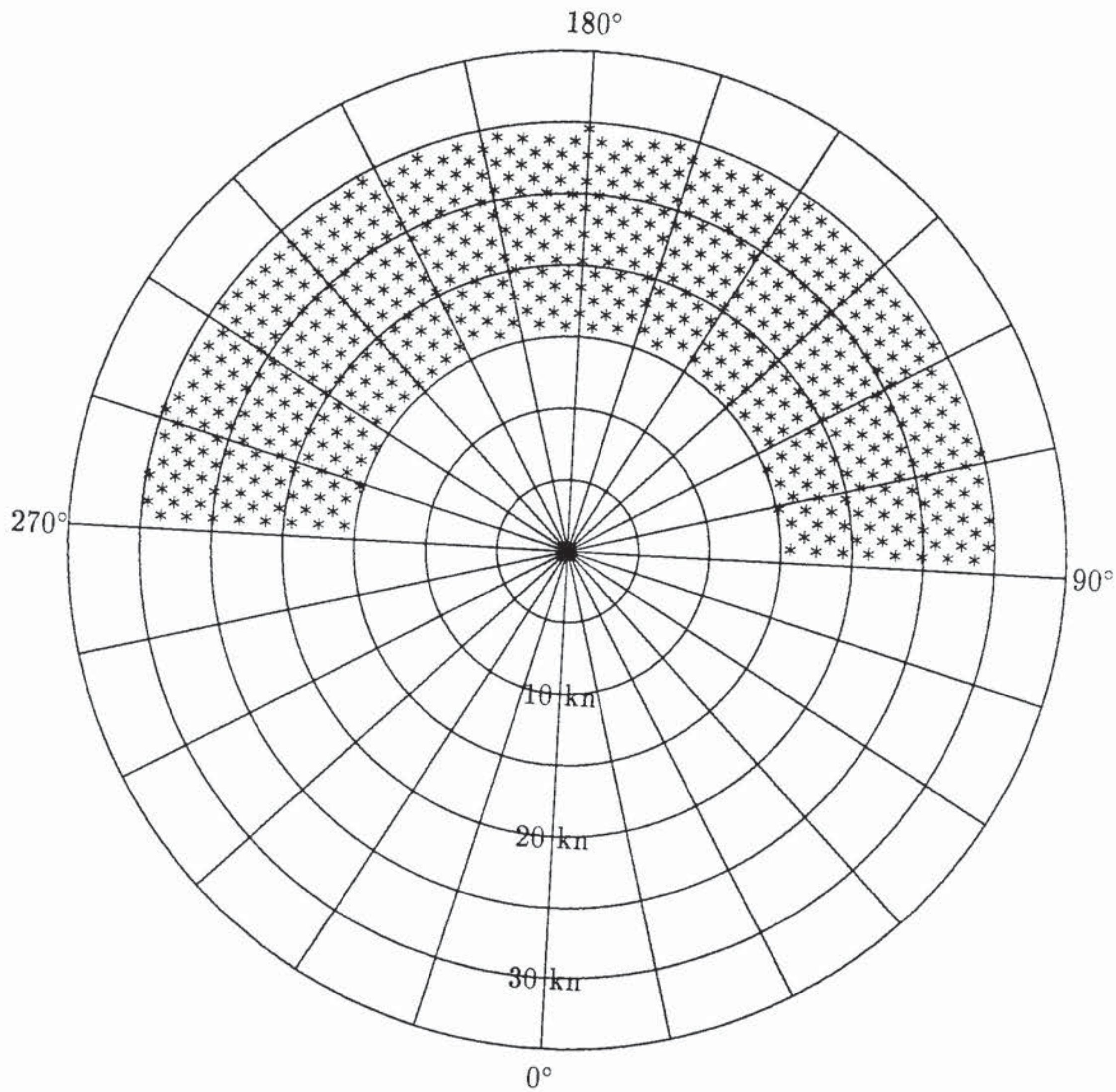

Figure 4: Non-optimum relative wind envelope. Shaded region is operable. Angles are ship heading relative to waves; head seas is 180°. Radial values are ship speed in knots.

envelope. Thus, possible degradation sources are equipment factors, human factors, and relative wind.

9.1 Example

A cruiser is undergoing VERTREP with the following assumptions:

1. Only VERTREP.
2. UNREP at 20 knots and all headings are possible.
3. Missile handling dolly on dry decks.
4. Use optimum relative wind envelope.

The cruiser VERTREP stations are given in Table 12. These points are used solely for calculating human factors criteria. The ship-to-ship interaction criteria are replaced by helicopter-to-ship criteria (touchdown difficulty) that are taken from helicopter landing criteria, Table 3.

Table 12: Vertical Replenishment pad locations for cruiser

Cruiser		
Station	Y(m)	Z (m)
3.5	0.0	12.2
17.0	0.0	10.7

The missile dolly limits come from Table 4. Maximum single amplitude slope limits for the dolly were converted to a single significant amplitude by multiplying by 0.53808, or 0.26904 for rms. The roll and pitch limits given in Table 4 represent a linear decrease in operability from 100 percent to 0 percent. If the operability versus response curve is modelled with a step function, 6 degrees (100 percent limit) should be used as the maximum amplitude to calculate the threshold value.

Table 13 is the final criteria set subject to operability code limitations because none of the limiting responses are duplicated. The human factors criteria are calculated at the VERTREP pads. The $\pm 30°$ relative wind envelope is used to ensure helicopter availability.

Table 13: Vertical Replenishment criteria.

Equipment factors			
Missile dolly slip angle	Roll	3.2°- 4.8°SSA	1.6°- 2.4°rms
	Pitch	3.2°- 4.8°SSA	1.6°- 2.4°rms
Touchdown difficulty	Abs. vert. disp.	1.4 m SSA	0.7 m rms
	Abs. vert. vel.	2.1 m/sec SSA	1.05 m/sec rms
Human factors			
Stumbling	MII	0.5/min	
	MSI	20% @ 4 hr	
	Submergence	0.5/hr	

10 CONCLUSIONS

A generic underway replenishment criteria set based on pallet slide angles has been replaced by criteria sets that systematically account for different sources of degradation. The degradation sources addressed here fall into three groups: ship-to-ship interaction, equipment factors, and human factors. Threshold values for the limiting motions associated with the degradations are given. The criteria sets are generated by examining all the possible limiting motions and taking the lowest threshold value for each. Different criteria sets are given for CONREP, FAS, and VERTREP.

The actual criteria set used also depends on the seakeeping and operability programs available. If a criterion is not calculated, it cannot be used, no matter how attractive. Using a seakeeping program that includes hydrodynamic interaction changes the response transfer functions, not the criteria sets.

A SEMI-LINEAR ROTATIONS

Rotations in the y-z plane are given by the following equations where ϕ is the roll angle and positive to starboard.

$$y^* = -z \sin\phi + y\cos\phi \tag{10}$$
$$z^* = y\sin\phi + z\cos\phi \tag{11}$$

Rotations in the z-x plane are given by the following equations where θ is the pitch angle and positive bow down.

$$x^* = z\sin\theta + x\cos\theta \tag{12}$$
$$z^* = -x\sin\theta + z\cos\theta \tag{13}$$

Rotations in the x-y plane are given by the following equations where ψ is the yaw angle and positive tc port.

$$x^* = -y\sin\psi + x\cos\psi \tag{14}$$
$$y^* = x\sin\psi + y\cos\psi \tag{15}$$

By combining these equations it is possible to develop three dimensional rotations; however, the final position depends on the order in which the rotations are made, so that roll-pitch-yaw is not the same as yaw-pitch-roll. Linearizing and semi-linearizing the equations makes them independent of rotation order.

The difference between points using the fully linear equations can sometimes result in the rotated distance being equal to the original difference. To avoid this the following three dimensional semi-linearized equations are introduced.

$$x^* = x\cos\psi\cos\theta - y\sin\psi + z\sin\theta \tag{16}$$
$$y^* = y\cos\psi\cos\phi + x\sin\psi - z\sin\phi \tag{17}$$
$$z^* = z\cos\theta\cos\phi + y\sin\phi - x\sin\theta \tag{18}$$

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Underway Replenishment (UNREP) is an important operation for sustained naval
operations. When evaluating Underway Replenishment operations, it is necessary to
consider the main factors that reduce operability. The main sources of degradation
identified in this report are: ship-to-ship interaction, equipment limits, and human factors.
This report examines these sources and provides a method for generating criteria sets for
operability evaluations. The example criteria sets developed represent the three different
aspects of UNREP and use the presented threshold values. Though comprehensive
analysis is suggested, various assumptions are made to allow analysis of cases where the
details of the ship configuration are unknown. The effects of these assumptions are
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